AC 2007-1242: COMPARATIVE EVALUATION OF ZIGBEE AND BLUETOOTH: EMBEDDED WIRELESS NETWORK TECHNOLOGIES FOR STUDENTS AND DESIGNERS

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Comparative Evaluation of ZigBee and Bluetooth: Embedded Wireless Network Technologies for Students and Designers

Abstract

Networked embedded system applications are becoming commonplace. Communication between common devices such as cell-phones, PDAs, cameras, printers are already available. These communication options can be expanded to include embedded systems in cars, homes, workplaces and other venues to provide users new ways to interact and be notified of important events.

New wireless solutions and standards have been developed to answer the user’s networking demands, including Bluetooth (IEEE 802.15.1) and ZigBee (based on IEEE 802.15.4). Selecting between these and other systems is a problem for students, instructional designers, and system developers. The capabilities and application domains of the various technical solutions must be clearly understood both in theory and practice. The specific requirements of application domains as diverse as cell phones, printers, smart homes or network system monitoring must also be clearly delineated to ensure successful project completion.

While system designers need to understand and incorporate these technologies in projects, instructional designers need to incorporate them in computer-oriented curricula to ensure the rising generation of computer students is well prepared.

This paper evaluates the wireless networking standards, Bluetooth and ZigBee. We discuss the intent of the standard developers, the pros and cons of each network type, appropriate applications, and the future of these standards. Recommendations are made for presentation in technological educational environments.

Introduction

Consumers are increasingly finding that networked embedded systems provide them with more powerful and flexible control over their working and personal environments. This leads to increased demand for these systems. Commonplace communication applications currently include devices such as cell-phones, PDAs, cameras, and printers. Soon consumers will expect their personal devices to communicate with other common objects such as home appliances, cars, and environment controllers.

Bluetooth[1] and ZigBee[2] each addresses the problem of allowing multiple, low-powered, embedded devices to communicate wirelessly within a short range. Each IEEE standard defines a physical layer and protocol stack, operates within the ISM band, and allows for omnidirectional, ad-hoc networking without a fixed infrastructure.

Despite these similarities, Bluetooth and ZigBee are generally not interchangeable as technology solutions. When selecting a wireless standard, developers must understand the intent, the characteristic pros and cons, and appropriate applications of each standard. Similarly educators must delineate these distinctions for their students.

Background

The IEEE 802.15 Working Group[3] develops standards related to Wireless Personal Area Networks (WPAN). A personal area network is a collection of short-range, interconnected devices (usually within a range of 10 meters). The devices of this network are generally portable; accordingly the devices are light-weight, relatively inexpensive, and battery-powered. This Working Group includes the wireless standard 802.15.1 (Bluetooth) and 802.15.4. 802.15.4 is the basis for the ZigBee standard, although ZigBee has other specified constraints. Each of these standards was designed to meet different needs. Each of these standards is promoted by different representative organizations.

The Bluetooth Special Interest Group (SIG)[4], founded in 1998, seeks to replace the cables of portable and fixed, voice and data application devices with wireless technology. Bluetooth allows a user's embedded devices to seamlessly recognize and exchange data with one another. For example, Bluetooth enables users to quickly and easily print pictures from a camera.

The ZigBee Alliance[5], formed in 2002, promotes the Zigbee standard. They have the goal of interfacing thousands of small, inexpensive, ultra-low power devices in a flexible network topology for home, commercial, and industrial applications. A simple example is that a user might activate the room lighting, a portable radio, and an iron with a single switch. A ZigBee-compliant system uses the 802.15.4 Physical Layer and Data Link Layer, and ZigBee defines the Network Layer and security mechanism. ZigBee also recommends a selection of application profiles to provide standard ways of developing compatible interfaces.

Learning Objectives

Introducing ZigBee and Bluetooth into a college-oriented, technical curriculum requires clear distinction between the different technologies. The learning objectives of such a course module would include the following:

1) Understanding the key concepts of each technology
2) Understanding the application domains of each technology
3) Being able to differentiate between the application domains for each technology

These objectives need to be incorporated into a complete computer technology educational system. Students learning these technologies need a background in basic computer architectures, basic networking, and some skills in configuring networks. At this stage of market acceptance of these technologies they could be used as an optional module in an existing networking or embedded systems course or could be expanded into a complete elective course in the curriculum.

The remainder of this paper will discuss the technical content that would need to be included to achieve the learning objectives.

Desirable Physical Characteristics

Several characteristics are crucial for the successful deployment of any portable device network: a licensed or license-free operating frequency, a data transmission rate and range suitable for the application, and an efficient power profile. In this section we discuss the importance of each of these characteristics and its relation to Bluetooth and ZigBee. A summary comparing Bluetooth and ZigBee is presented in Appendix A.

Operating Frequency

The choice of frequency band is an important factor in system design. The frequency selection affects the data transmission speeds, the likelihood of interference with other devices, the complexity of radio transceivers, and the cost of purchasing license rights from the FCC. IEEE 802.15 and 802.11 devices operate within two of the FCC's license-free ISM bands: 900 MHz, and 2.4 GHz.

Bluetooth operates at 2.45 GHz using a spread spectrum, Frequency Hopping Spread Spectrum (FHSS) signal of 79 1MHz pseudo-randomly ordered channels. Adaptive Frequency Hopping (AFH) allows Bluetooth to detect and exclude frequencies in use by other devices and select channels to minimize interference[6].

ZigBee may operate at 868 MHz, 915MHz, or 2.4 GHz using a Direct Sequence Spread Spectrum (DSSS). Developers may select the band which best suits the speed and local frequency regulations of their application. ZigBee utilizes CSMA-CA – an automatic, random delay between packet transmissions – to reduce packet collisions.

These two, different approaches to frequency operation is a major key in distinguishing Bluetooth applications and ZigBee applications. Bluetooth's AFH ensures minimal frequency interference, transmission security, and a high Quality of Service (QoS) at the expensive of processing and battery power. Conversely, ZigBee conserves power at the expense of its QoS. ZigBee is not appropriate for applications requiring a high QoS such as audio streaming.

Data Transmission Rate

The data rate indicates how quickly a bit can be transferred from one device to another, which affects the amount of bandwidth that will be introduced within application communications. The modulation technology, encryption techniques, packet length, and radio frequency combined influence the data transmission rate. Bluetooth 1.2 achieves a maximum data rate of 1.2 Mbps, and Bluetooth 2.0+EDR (Enhanced Data Rate) achieves up to 3 Mbps[7]. ZigBee can achieve a data rate of 250Kbps at 2.4GHz (16 Channels), 40 Kbps at 915 MHz (10 channels), and 20Kbps at 868Mhz (1 channel) [8]. Bluetooth is over-specified for applications requiring small packets and infrequent communication, yet it is ideal for file transfers and data exchange. Users may find transferring a file over ZigBee unreasonably slow, yet the same user will not notice the time necessary to transfer text between devices.

Data Transmission Range

A wireless device must be within range of a second device in order to exchange data. The data range is influenced by existence of interferences, the radio transceiver, and the operating frequency. The device communication range of Bluetooth further varies depending on the radio class selected by the developer. The developer may choose one of three classes: Class 1 radios transmit across 1 meter, Class 2 across 10 meters, and Class 3 across 100meters[7]. Similarly, ZigBee can transfer data over 1 to 100 meters[8]. The ZigBee specification, which allows mesh networking, may transmit data to any network node providing that a routing path can be established between nodes in the intervening mesh. Routing is performed automatically by the system. When selecting a standard, the anticipated user-object interactions must be defined. ZigBee excels when a device must communicate with an out-of-range, but routable device. If a distributed network is not expected, the two standards are equivalent.

Power Profile

Portable embedded devices rely on batteries to provide power, so a standard's ability to conserve power is a crucial consideration. The duty cycle and the power required to join a network and access the channel influence the efficiency of standard's power profile.

ZigBee operates on a very low duty cycle of $< 1\%$ [8] to prolong the primary battery life. (AA batteries are expected to last years on a ZigBee device[9].) To further reduce power consumption and reduce latency due to inactive nodes, devices require only 30 milliseconds to join a network[10] and a slave can typically transition from a sleep state to an active state in 15 ms[8].

Bluetooth emphasizes availability and ad hoc networking over power conservation. A Bluetooth Device must remain awake to constantly be on alert and ready to join networks[6]. Further, Bluetooth devices require 20 seconds to join a network and 3 seconds to transition from an inactive to an active state[11]. Since Bluetooth power is constantly on the power drain is considerably higher than that of ZigBee.

Like the operating frequency, the power profile is a major key in distinguishing Bluetooth and ZigBee applications. Applications desiring quick discovery and access to existing networks are best served by Bluetooth. Applications requiring long battery lives, delayed ad hoc networking, and minimal user maintenances of batteries are best served by ZigBee.

Desirable Network Characteristics

Available network topology options influence which applications a network model is most suitable. In this section we discuss the topology and scalability of Bluetooth and ZigBee.

Bluetooth Network Topology

Bluetooth devices communicate within a piconet – a group consisting of one master, one to seven slave devices, and up to 255 parked (i.e. inactive) slave devices all occupying the same physical channel. The master device provides the common clock and frequency hopping pattern references to the slaves. Full-duplex transmission is achieved through time-division duplexing

(TDD)[6]. A piconet master communicates with each active slave during each multiplexed time slot in a round-robin-like fashion.

Slave devices may only communicate with the master device and never directly with another slave; however a slave device may participate in one or more piconets (a scenario known as a scatternet). A single device may never be master of more than one piconet. Unfortunately, the Bluetooth standard does not define any networking between the piconets within a scatternet, but applications may be designed to facilitate such communication.

Bluetooth's inability to allow peer-to-peer communications limits its usefulness in distributed networks. Further, Bluetooth's active device limitation and limited 48-bit addresses constrains a Bluetooth network's scalability compared to ZigBee's 64-bit addresses. Bluetooth is not suitable for applications anticipating a large number of interconnected nodes. Bluetooth is designed for most WPAN applications which involve few embedded devices.

ZigBee Network Topology

ZigBee defines three device types: ZigBee Coordinator (ZC), ZigBee Router (ZR), and ZigBee End Device (ZED). A network must contain at least one coordinator device as the coordinator initiates the networking formation and participates in the routing of messages. The router device actively routes messages between devices. The end device does not route messages to other devices[9].

The ZigBee standard allows for star, cluster tree, or mesh topology configurations of up to 65,000 nodes[12]. The mesh topology allows for peer-to-peer communication (regardless of device type). The mesh topology creates a very robust system for as nodes are removed from the network (by design or by failure) messages may still be routed through other devices. The high scalability and robust nature of ZigBee mesh networking lends itself to large and distributed networks prone to device failure such as wireless sensor networks.

Desirable Application Support Characteristics

Application support characteristics ease the development of WPAN, security mechanisms and profiles. In this section we discuss the importance of each characteristic and its inclusion within Bluetooth and ZigBee.

Security Mechanisms

Wireless communication is inherently public. Authorized entities have access to the network data while eavesdroppers have equal access to unprotected data. Network data must be protected to prevent data and identity theft.

Bluetooth users may establish a PIN, also known as a passcode or link key, for each of their devices. Pairing, the process of establishing a logical channel, requires that two Bluetooth devices permanently exchanges their PINs and permanent addresses. The pairing relationship is terminated when a device's PIN is changed or the pairing is deleted from one (or both) of the devices. Bluetooth devices cannot communicate without an established pairing. Additionally, Bluetooth provides built-in, optional 128 bit encryption.

The ZigBee Coordinator distributes network authentication keys to new network nodes[10]. The application designer must determine what conditions are required to verify the identity of new network nodes otherwise the Coordinator indiscriminately distributes the keys. The ZigBee specification also provides the necessary mechanisms for packet freshness timers and AES 128-bit encryption.

Profiles

Profiles ensure interoperability between devices regardless of developer or manufacturer which influences market adoption. A profile suggests user-interface formats, defines dependencies on other profiles, identifies protocol stack configurations, and describes device-to-device behavior. The use of a profile ensures that a device may communicate with third party devices. Bluetooth incorporate profiles within its specification. Examples of existing profiles[6] include Audio/Video Remote Control Profile (AVRCP), Basic Printing Profile (BPP), Cordless Telephony Profile (CTP), File Transfer Profile (FTP), Headset Profile (HSP), and Intercom Profile (ICP). ZigBee publishes optional profiles outside of its specification, and a device with a manufacturer-specific profile is still ZigBee-compliant. Available and in-progress ZigBee profiles include: Home Automation (HA), Industrial Plant Monitoring, Commercial Building Automation, and Wireless Sensor Networks[9].

Other Considerations

When selecting between two wireless standards embedded device developers cannot only rely on the standard's specification. The industry and consumer adoption, the implementation expense, and other competing standards all influence the final selection. In this section we discuss the other considerations to be considered when choosing between Bluetooth and ZigBee.

Industry and Consumer Adoption

The industry and consumer adoption of Bluetooth is thriving. Over 6,000 companies are members of the Bluetooth SIG[13]. Notable members include: Ericsson, Intel, Microsoft, Nokia, and Toshiba. The Bluetooth SIG claims that 12 millions Bluetooth devices are shipped per week and are in the hands of one billion consumers[13].

The ZigBee Alliance roster includes more than 200 promoter-grade companies including Freescale, Honeywell, Mitsubishi Electric, Motorola, Samsung, and Philps[14]. ZigBee reports that Alliance members have shipped over 10,000 Developer Kits and processed 29,000+ free downloads of the ZigBee specification. They consider these numbers to be evidence that for-market products are being developed and ZigBee will have a strong market growth[15]. At this time, few ZigBee products are available on the market; the first ZigBee-certified products became available in November, 2006[15]. Currently consumers may purchase Zigbee-based home automation systems from Control4 and Eaton.

The ZigBee Alliance distribution numbers pale in comparison to those of the Bluetooth SIG; however, Bluetooth has experienced several more years of market availability than ZigBee. Market analysts forecast 273 million ZigBee wireless sensing network nodes in 2010[10].

Membership Expense

An entry level membership in the Bluetooth SIG (i.e. adopter) is free, but unavailable to students. The adopter level includes access to Bluetooth.org, usage of the Bluetooth specification in products, and use of the Bluetooth logo. A corporate membership (i.e. associate) Bluetooth SIG starts at $7,500/year for small companies and $35,000/year for large companies; this membership level also allows participation in Bluetooth specification development[16].

An entry level (i.e. adopter) ZigBee alliance membership is $3,500/year. The adopter level includes access to the final, approved ZigBee specifications; allows attendance at the ZigBee Alliance Interop events, workshops, and developer conferences; permits the receiving of ZigBee Alliance marketing collateral; allows use of the ZigBee logo; and provides access to exclusive ZigBee web pages, task group email reflectors, teleconferences, and documents. Companies may become participants for $9,500/year or promoters (which include a seat on the Board of Directors and voting rights) for $40,000/year[17].

Chipset Cost

The cost of Bluetooth chips is under $3 per device[18]. Comparatively, as of 2006, the retail price of a Zigbee-compliant transceiver is approaching $1, and the price for one radio, processor, and memory package is about $3[19]. Thus the costs are very comparable and not a major disseminating factor for choosing between them. The cost of both chips is expected to continue to fall as volume increases.

Anticipated Future Competition

The IEEE 802.15.3 task group members expect their Ultrawideband (UWB) standard to become a USB cable replacement and PAN. UWB will transmit data over several frequencies (similar to the way current USB technology transmits over several wires). The finalization of UWB and industry adoption are in doubt as neither the UWB Forum nor the WiMedia Alliance has garnered the required 75% majority agreement required to ratify the standard. The WiMedia Alliance argues for direct-sequence ultrabandwidth while the UWB Forum multiband orthogonal frequency-division multiplexing[20] (OFDM); the disagreement[21,22] stems from radio interference with existing devices, ungoverned use of the frequency spectrum in Europe and Asia, power consumption, chipset expense, and backward-compatibility with UWB 2.0. Further compounding the completion of the 802.15.3 standard, companies have begun to create their own solutions, such as Freescale's CableFree[21,23], and WiMedia expects the first certified products based on their technology to enter the consumer market in early 2007[22]. Further, WiMedia is seeking standardization for its OFDM technology from Ecma International and the International Standards Organization[22]. This division and uncertainty bodes ill for future compatibility and user adoption difficulties.

As of late 2006, Nokia is developing something they call Wibree[24]. Few technical details are available to describe the new communication definition. The technology is recommended for applications where Bluetooth would be too large, too powerful, or too expensive. Wibree is Bluetooth-compatible, and Wibree appears to be a faster version of ZigBee (Wibree's intended 1 Mbps vs. ZigBee's 250 kbps). Wibree is recommended for devices where Bluetooth would be overkill, ZigBee wouldn't provide enough gusto, and Bluetooth-compatibility is desirable (e.g. watch). Should Wibree fulfill Nokia's marketing claims the technology may replace both Bluetooth and ZigBee for simple, personal embedded devices.

Existing Applications

To further illustrate the application domains for these two technologies consider the following examples of working systems in each technology.

Bluetooth

- Cell phones promote interoperability between multiple devices including head sets and desktop computers regardless of manufacturer
- Headsets stream real time audio data with a high quality of service headsets
- Nintendo Wii controllers[25] transmit button and real-time motion data with a high quality of service
- Printers requiring file transfer and interoperability between devices regardless of manufacturer

ZigBee

- Bird burrow monitoring devices[26] allow researches to collect data and route network edge data to a centralized point
- Wireless Sensor Networks for Emergency Navigation[27] uses the mesh networking capabilities to map the shortest path through safe areas and simultaneous support of potentially hundreds of devices
- Water Pressure Sensor for Firefighters[28] uses ZigBee to report water pressure at the end of the hose back to the fire truck. Routing abilities are incorporated by placing a mote every so often along the fire hose.
- Printer[29] management by reporting temperature, toner level, and paper jams

Conclusions

Bluetooth surpasses ZigBee in data speeds, ad hoc networking abilities, frequency interference avoidance, and standardized application profiles. Bluetooth is ideal for file transfers, data exchange, and data streaming between a small numbers of embedded devices. Bluetooth is best suited for facilitating communication between computer peripherals and a master device for example mice, keyboards, PDAs, cell phones, cameras, and visual interfaces.

If your application needs a predominance of the following features choose a Bluetooth system

Essential

- real-time data streaming (i.e. audio or video streaming)
- high quality of service (QoS) guarantee

Preferential

- nodes are required to actively identify compatible devices, determine their available services, and establish a semi-permanent relationship
- guaranteed interoperability of like-devices between differing manufacturers or developers

ZigBee outstrips Bluetooth for devices requiring long battery lives (in the order of months and years) for peer-to-peer networking, and for node failure within a network. ZigBee is the best choice for applications requiring small packets and infrequent communication throughout a distributed mesh network.

If your application needs a predominance of the following features choose a Zigbee system

Essential

- simultaneously network support hundreds of devices
- routing messages to a device out of the direct transmission range of the sending device

Preferential

- multiple monitoring or sensing device

In summary the application markets for both of these standards are growing. They have different but overlapping application domains. An understanding of the underlying technologies and application domains is a valuable knowledge-base for modern technology students in computer disciplines.

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Appendix A – Comparative Summary of Desirable Characteristics

The data contained within this table was collected from many sources[8,11,12].

Characteristic	**ZigBee**	**Bluetooth**
Application Focus	Monitoring & Control	Cable Replacement
Market	Text	Internet/Audio
Air Interface	DSSS@868 MHz, 915MHz, 2.4GHz ISM	FHSS@2.4GHz ISM
Transmission Range	Indoors 10-100m Outdoors up to 400 m	Indoors 10m Outdoors 100+ m dep. On radio
Data Rate	up to 250 Kbsp	up to 1Mbps
QoS	No	yes
Battery Life	months, years	Days
System Resources	4 KB – 32 KB	250 KB+
Network Topology	Adhoc, star, mesh	Adhoc piconets
Nodes/Master	65,000/1	7/1
Scalability	Very High	Low
Latency	enumeration 30ms wakeup 15ms channel access 15 ms	enumeration up to 10s wakeup 3s channel access 2ms
Resilience	Very High	Medium
Security	128 bit AES, user-definable	64 bit, 128 bit